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CHAPTER 8.3
OTHER METALLIC COATINGS

PART 1
HOT-DIP METALLIC COATINGS

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THE PROCESS

Hot-dip metallic coatings are applied by immersing the workpiece in a bath of molten metal. Typical of all these processes and most prevalent is that for applying molten zinc to fabricated steel.

The first step involves cleaning (See Chap. 8.1). Rust, scale, oil, paint, and other surface contaminants must be removed by a suitable preliminary treatment. Caustic-bath degreasing followed by chemical cleaning in an acid bath is common. Ferrous castings are often shot-blasted and pickled.

Before entering the molten-zinc bath, the material is given a fluxing treatment by immersing it in an aqueous-flux solution, by maintaining a flux blanket on the bath, or by a combination of both techniques.

Coating involves immersion in the molten metal for periods ranging from a fraction of a minute for small objects such as fasteners to several minutes for structural shapes. The bath temperature for galvanizing (zinc coating) is about 450°C (842°F), and for aluminum approximately 700°C (1290°F). When an object that exceeds the size of the molten-metal bath is to be coated, a technique known as *double dipping* may be employed if the item cannot be redesigned to fit into the bath in a single dipping operation.

Postcoating treatment varies according to the needs of the coated component. Slow cooling, quenching, conversion coating, and painting (preceded by prepainting treatments) may be employed.

Figures 8.3.1, 8.3.2, and 8.3.3 illustrate hot-dip-coating operations for steel structural members.

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CHARACTERISTICS

When properly selected, hot-dip metallic coatings provide excellent long-term corrosion protection for the coated object. They provide this in two distinct ways: (1) The coating functions as a barrier that shields the base material. (2) The coating may provide sacrificial galvanic protection. Coatings of metals higher in the electromotive series than the basis metal will corrode in preference to the basis metal. Protection will be provided even if there is a break in the continuity of the coating. Figure 8.3.4 lists common metals in accordance with their places in the electromotive series.

For atmospheric corrosion, zinc exhibits a linear relationship between weight of coating and both expected service life and severity of the environment. (See Fig. 8.3.5.)

In general, the size of objects that can be hot-dip-coated is limited by the size of melting pot that is available. Hot-dip-tinning operations are normally confined to

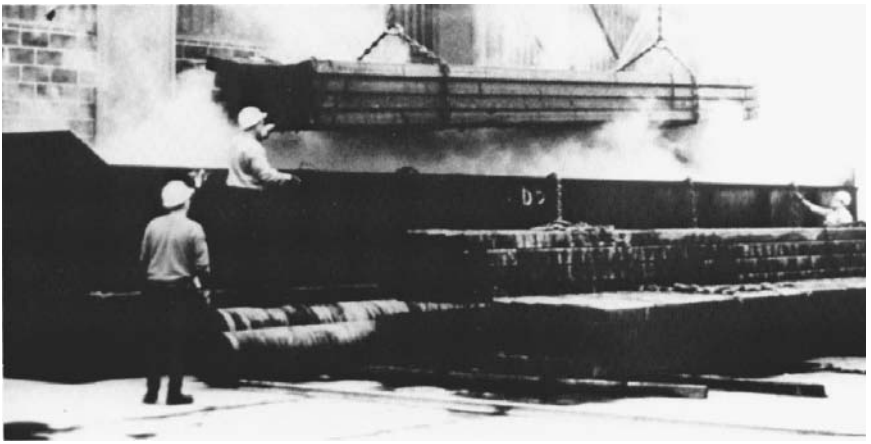

FIGURE 8.3.1 The galvanizing process. Caustic cleaning to remove dirt and organic contaminants is a first step. (*Courtesy St. Joe Lead Company.*)

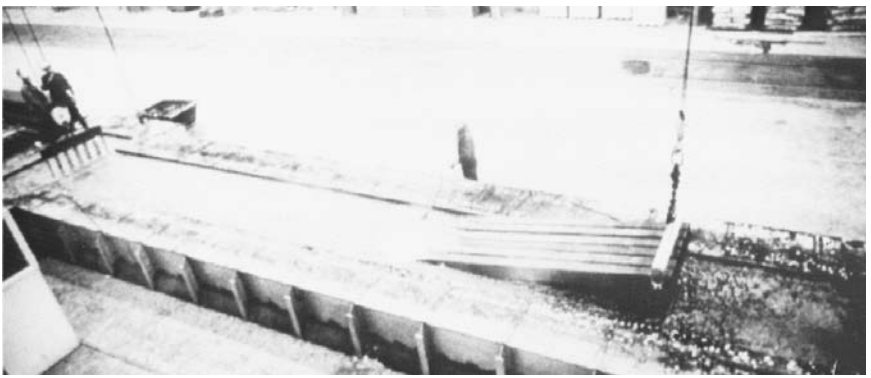

FIGURE 8.3.2 In galvanizing, the steel is immersed in molten zinc covered by a flux layer that ensures a chemically clean surface. (*Courtesy St. Joe Lead Company.*)

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OTHER METALLIC COATINGS

FIGURE 8.3.3 The galvanized steel is withdrawn from the clean molten-zinc bath. The zinc layer is now metallurgically bonded to the steel. (*Courtesy St. Joe Lead Company.*)

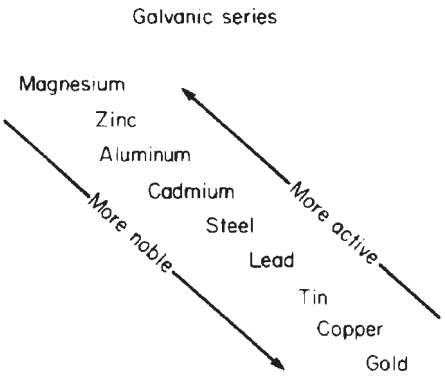

FIGURE 8.3.4 An abbreviated galvanic series ranking metals according to their tendency (activity) to enter solution.

small pieces. At the other end of the scale, galvanizing kettles approaching 18 m (60 ft) in length are in service.

Coating thickness varies by process as well as by coating type. In the case of hot-dip-galvanized material coating, thickness is customarily specified in grams per square meter or ounces per square foot as either a minimum or an average coating weight. Normal values range from about 150 to 920 g/m^2 (0.5 to 3 oz/ft^2). This is equivalent to a thickness of 0.01 to 0.13 mm (0.0004 to 0.005 in).

Figure 8.3.6 illustrates typical components protected by hot-dip coatings.

ECONOMIC PRODUCTION QUANTITIES

Depending on the degree of material-handling sophistication in the hot-dip-coating plant, hot-dip-applied coatings can be applied on either a short-run or a mass-pro-

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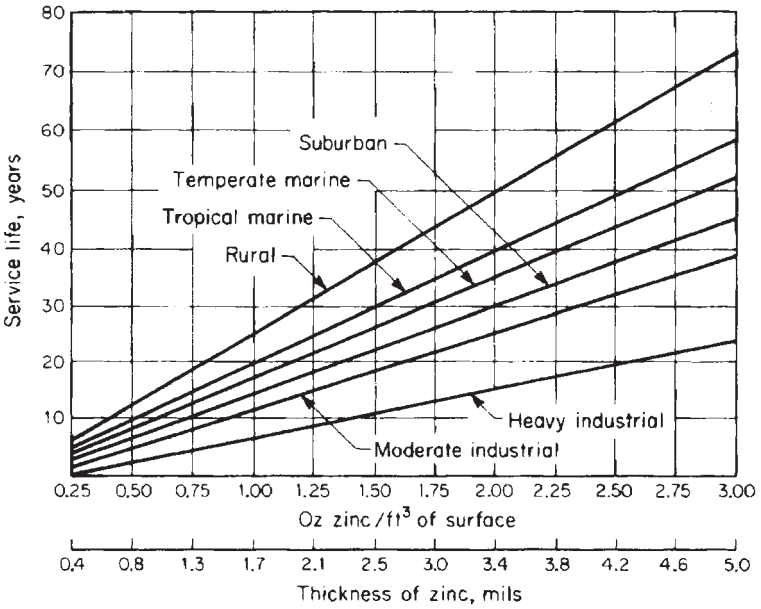

FIGURE 8.3.5 Anticipated life of zinc coatings in the atmosphere. (*Courtesy American Hot Dip Galvanizers Association.*)

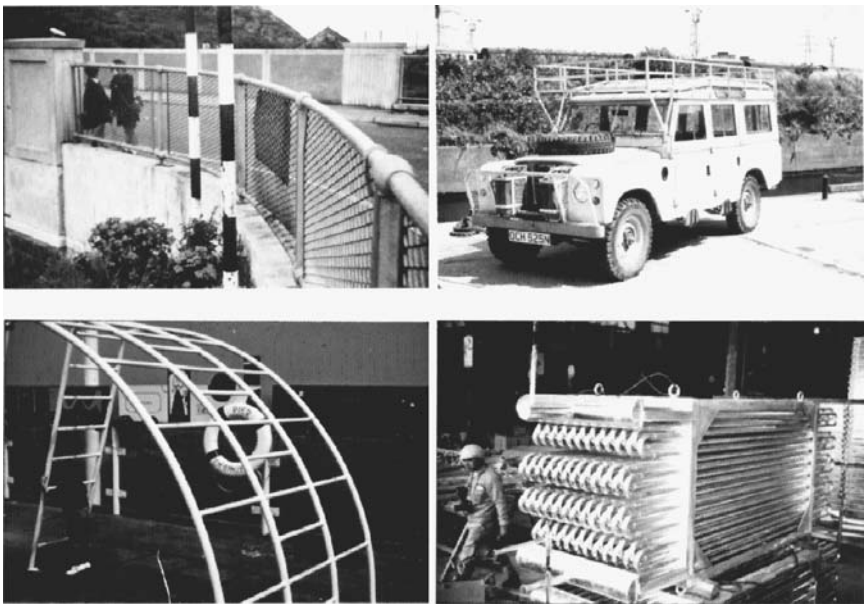

FIGURE 8.3.6 Typical applications of galvanized coatings. (*a*) Fence components. (*b*) Land-Rover roof rack. (*c*) Playground equipment. (*d*) Tubular condenser. (*Courtesy American Hot Dip Galvanizers Association.*)

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duced basis. In judging whether the hot-dip process is economical, engineers should keep in mind that coaters normally use a throughput of tons of material per hour in their kettles as their measure of equipment utilization. A smaller kettle operation may operate on a completely different economic basis than a larger kettle operation.

Thus, for short runs of small objects, a rule of thumb would be to investigate costs with a hot-dip-coating applicator having an efficient operation and a kettle suited to coating the object in question. However, it must be noted that economical production quantities will vary from coater to coater, as will costs to handle small lots.

SUITABLE MATERIALS

Substrates

By far the most common substrate materials for hot-dip-applied metallic coating are cast iron and steel. In some specialized situations, materials such as high-strength low-alloy steel also may be used.

In selecting a steel substrate material, it is most beneficial if the designer keeps the following considerations in mind:

1. Steels containing carbon below 0.25 percent, phosphorus below 0.05 percent, and manganese below 1.35 percent, either individually or in combination, are normally most suitable and will usually develop a "typical" galvanized coating when conventional galvanizing techniques are used, provided the silicon is 0.05 percent or less or between 0.15 and 0.30 percent.
2. Combinations of different steel materials and different manufacturing processes (e.g., welded, cast, or hot-rolled) may produce coatings of different thicknesses and with a variable surface appearance. While this may not be detrimental to the corrosion performance of the coating for many applications, the designer and fabricator should be aware of this circumstance in advance.
3. The effect of the heat of the molten bath on the substrate material should be considered. If the steel is susceptible to strain-age hardening owing to being severely cold-worked, it may be brittle after it has been coated because of accelerated aging. Very often, strain-age embrittlement is an indication that the material was incorrectly chosen or that it was subjected to extreme fabrication conditions. In this regard, it is best to select steels having a low transition temperature.

Coatings

Zinc, aluminum, tin, lead, and terne (lead alloyed with 10 to 20 percent tin) are commonly used for hot-dip coatings. Generally, zinc, aluminum, and terne perform well in providing corrosion protection under most atmospheric conditions. For other service conditions such as are encountered in soils or aqueous media, the choice can involve complex technical considerations.

Aluminum is considered to be resistant to distilled and ordinary fresh waters, hard as well as soft, under most conditions. However, although hot-dip aluminum coatings can be applied provided proper care is taken, they are generally not suited for fabricat-

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ed objects and job-shop operations. This is due to the formation of a tenacious film of aluminum oxide which interferes with the iron-aluminum interface during the dipping operation.

Lead and tin do not provide galvanic protection, but lead coatings may be very resistant to soils which are highly aggressive to zinc coatings. Lead has good resistance to sulfuric and hydrochloric acids, brines, etc. However, owing to its tendency to coat unevenly and to pit, it is not used extensively as a coating for steel in the atmosphere or in most soils.

Alloying lead with other elements such as tin, antimony, cadmium, mercury, and arsenic produces coatings that have been used with success. Terne coatings are applied in much the same manner as are hot-dip tin coatings.

DESIGN RECOMMENDATIONS

Access and Drainage of Molten Metal

To achieve complete corrosion protection, the molten coating metal must be able to flow freely to all surfaces of the part. Coating hollow sections greatly reduces the possibility of hidden corrosion at some later date. Some general principles to ensure full, uniform coverage are the following:

1. Holes for venting and draining should be as large as possible. Full cutouts are preferred for pipe assemblies and base plates.
2. Holes for venting and draining should be diagonally opposite at the high and low points of the fabrication as it is suspended for the coating process.
3. Internal and external stiffeners, baffles, diaphragms, and gussets should have their corners cropped to aid the free flow of molten metal.

Figures 8.3.7 through 8.3.9 illustrate these guidelines.

Minimizing Distortion

Because of the temperatures involved in the coating process, there can be stress relief, which can result in distortion. To minimize distortion, design engineers should observe the following recommendations:

1. When possible, use symmetrical rolled sections in preference to angle or channel frames.
2. Specify the minimum welds possible in order to reduce thermal stresses.
3. When bending component members, use the largest acceptable radii, not less than 3 times material thickness.
4. When possible, build assemblies and subassemblies in units suitable for single dipping.
5. The extent to which an assembly will distort is largely dependent on the design and can be appreciably reduced by avoiding combinations of extremes in weight and

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OTHER METALLIC COATINGS

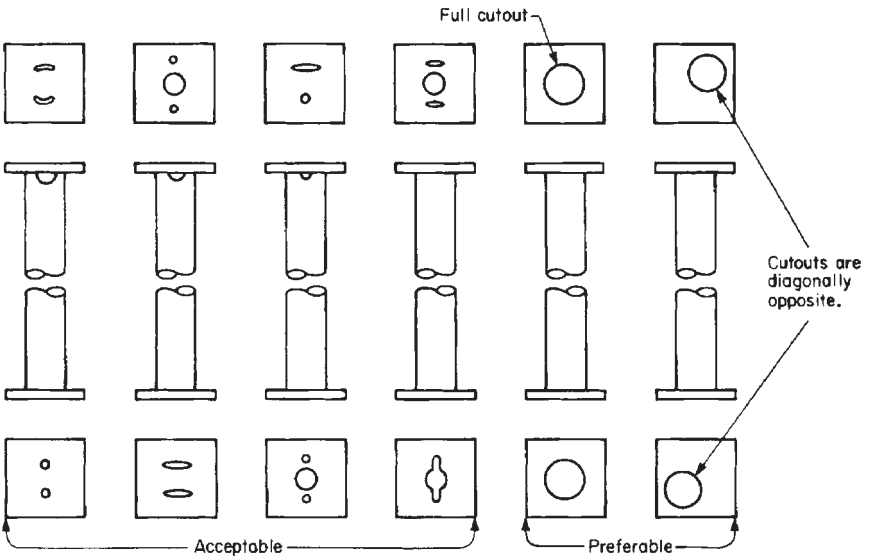

FIGURE 8.3.7 Pipe-column venting. Any of the possible venting methods shown is acceptable. Vent holes should be off center, as close to the inside wall of the pipe as possible, as large as possible, and diagonally opposite the ends of the pipe plates.

cross section of structural members such as shown in Fig. 8.3.10.

Screw Threads

When the product to be hot-dip-coated includes threaded members, the pitch diameter must be adjusted to allow for the thickness of the coating. Recommended oversize tappings for female threads to be used with galvanized bolts are given in Table 8.3.1. On threads greater than 40 mm (1½ in) in diameter, it is often more practical, design and load requirements permitting, to cut the male thread 0.8 mm (0.032 in) undersize so that a standard tap can be used on the nut. Threads on long rods and faces of flanges may be brushed while hot. This reduces the coating thickness but allows a better mechanical fit. Small threaded parts can be centrifuged to remove excess zinc and produce smoother coatings.

Postcoating Treatments

If designers anticipate that galvanized components will be subjected to conditions con-

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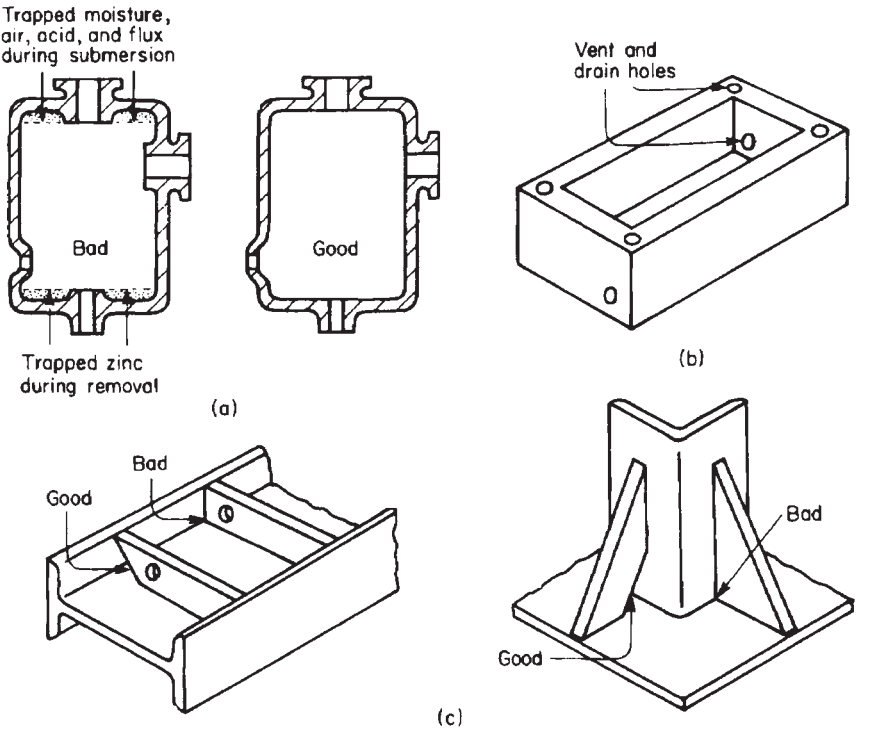

FIGURE 8.3.8 Venting and draining of enclosed and semienclosed products. (*a*) Tank design should always provide for flush interiors to prevent trapped moisture, air, acid, and flux during submersion and trapped zinc during removal. (*b*) When a housing design requires return flanges, provide drain holes in all corners and through holes for venting in at least two opposite surfaces. (*c*) When gussets and stiffeners are used, generous clipping provides for free drainage.

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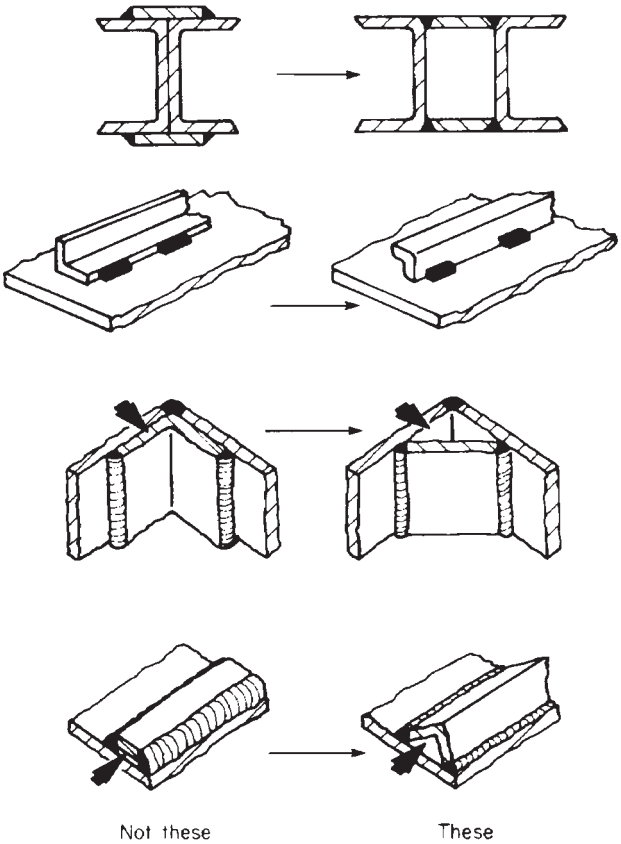

FIGURE 8.3.9 When designing welded assemblies to be hot-dip-coated, provide space for free access of the molten-metal bath to all surfaces.

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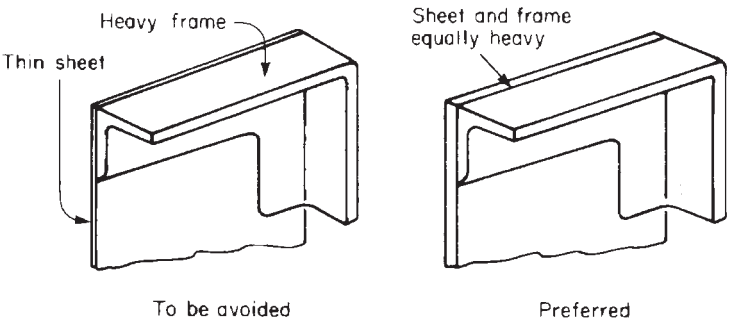

FIGURE 8.3.10 To avoid distortion, avoid a combination of extremes in the weight and cross section of structural members.

TABLE 8.3.1 Recommended Oversize Tapping for Threaded Holes to Be Used with Galvanized Bolts (ASTM A563)

Bolt or stud diameter, mm (in)	Minimum oversize tapping required, mm (in)
11 (7/16) and smaller	+0.4 (+0.015)
Over 11 (7/16) to 25 (1)	+0.5 (+0.020)
Over 25 (1)	+0.8 (+0.032)

ducive to wet-surface stain (e.g., prolonged stacking in a moist or wet environment), they should specify a protective postcoating treatment. One of the most effective of such treatments involves immersion of the workpiece in a solution of sodium dichromate. Galvanized material also can be painted if the proper pretreatment steps are carried out.

Coating-Thickness Recommendations

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TABLE 8.3.2 Recommended Coating Weight for Hot-Dip-Galvanized Products (ASTM Specifications)

Class of material	ASTM specification	Minimum weight of zinc coating of any individual specimen, g/m^2 (oz/ft^2)
Products fabricated from rolled, pressed, and forged steel shapes, plates, bars, and strip	A123	
3–5 mm (1/8–3/16 in) thick		550 (1.80)
6 mm (1/4 in) and heavier		610 (2.00)
Hardware	A153*	
Class A: castings—gray iron, malleable iron, steel		550 (1.80)
Class B: rolled, pressed, and forged articles (except those that would be included under Classes C and D)		
Class B-1: 5 mm (3/16 in) and over in thickness and over 200 mm (8 in) in length		550 (1.80)
Class B-2: under 5 mm (3/16 in) in thickness and over 200 mm (8 in) in length		380 (1.25)
Class B-3: 200 mm (8 in) and under in length and any thickness		340 (1.10)
Class C: bolts and drivescrews over 9.5 mm (3/8 in) in diameter and similar articles; washers 5 and 6 mm (3/16 and 1/4 in) thick		305 (1.00)
Class D: screws, stove bolts, and bolts 9.5 mm (3/8 in) and under in diameter, rivets, nails, and similar articles; washers under 5 mm (3/16 in) thick		260 (0.85)
Assemblies	A386	
Class A: castings—gray iron, malleable iron, steel		550 (1.80)
Class B: rolled, pressed, and forged steel		
Class B-1: 5 mm (3/16 in) and over in thickness		550 (1.80)
Class B-2: under 5 mm (3/16 in) in thickness		380 (1.25)
Class C: bolts and drivescrews over 9.5 mm (3/8 in) in diameter and similar articles		305 (1.00)
Class D: bolts and drivescrews 9.5 mm 3/8 in) and under in diameter and similar articles		260 (0.85)
High-strength bolts	A153, Class C	305 (1.00)
Tower bolts	A394	305 (1.00)

*Length of the piece, stated in Classes B-1, B-2, and B-3, refers to the overall dimension and not to its developed length; 1 oz zinc/ft^2 surface corresponds to coating thickness of 0.043 mm (0.0017 in).

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Table 8.3.2 presents ASTM specifications for zinc-coating-weight thickness in job coating applications. Normal minimal coating thicknesses for precoated sheet run from 0.05 to 0.08 mm (0.002 to 0.003 in) for aluminum, 0.006 to 0.026 mm (0.0002 to 0.001 in) for terne, and 0.007 to 0.043 mm (0.0001 to 0.0017 in) for zinc.

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OTHER METALLIC COATINGS

PART 2
THERMAL-SPRAYED COATINGS

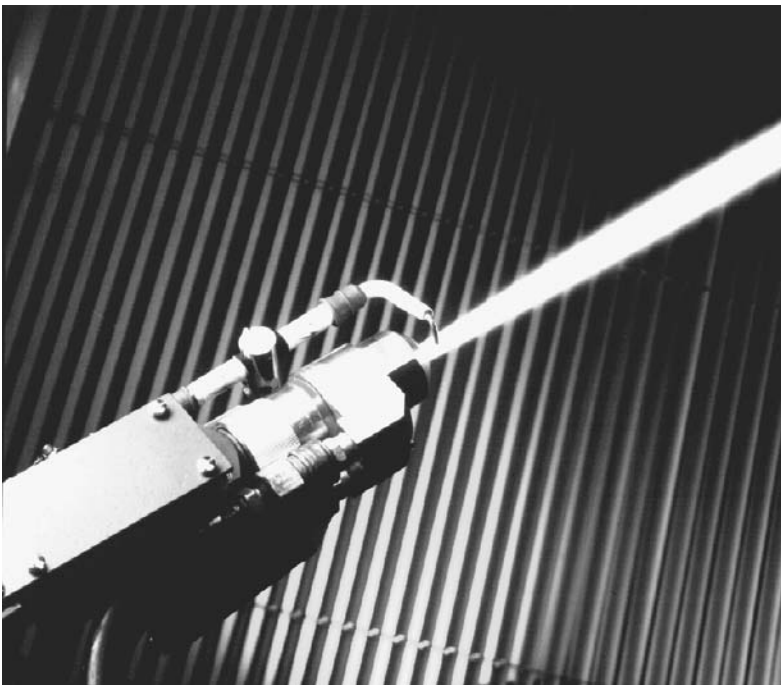

FIGURE 8.3.11 An HVOF (high-velocity oxygen fuel) gun in operation. (*Courtesy Sulzer Metco.*)

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THERMAL-SPRAYING PROCESS

In the thermal-spray-coating process (sometimes called *flame-spray-coating process*) a gun is used which, with either a combustion flame, a plasma arc, or an electric arc, melts and propels metal, ceramic, or other material in finely divided form toward the

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article to be coated. The particles strike the object and flow into thin, flat droplets that interlock and overlap as they solidify. Multiple passes are usually necessary to build the coating to the desired thickness.

Wire metallizing is the oldest and best-established thermal-spraying method. Wire is fed axially through the gun and through a ring of flame (oxygen and acetylene, propane, or other fuel gas), which melts the wire tip. An outer sheath of compressed air "atomizes" the molten metal to droplets roughly 10 to 100 μm in diameter and propels these to velocities ranging from 91 m/s (300 ft/s) to 240 m/s (800 ft/s). The droplets strike the substrate at about 10 cm (4 in) to 25 cm (10 in) from the gun and flatten out while freezing, thus building up a coating.

Powder is sprayed similarly with a combustion flame-spray gun. It is carried from a hopper and fed axially through the ring of flame. The flame accelerates the molten particles to about 90 m/s (300 ft/s).

In the plasma arc-spray gun, a direct-current arc similar to a welding arc heats a gas (argon or nitrogen in combination with hydrogen or helium) above 4400°C (8000°F), at which point it is dissociated and partially ionized to create the plasma state, which issues from the nozzle. Power is usually fed radially into the plasma near the exit point.

The electric-arc process also has an electric arc as the heat source but uses wire instead of powdered metal. The wire serves as the electrode.

Detonation-gun spraying, another process variation, employs a mixture of nitrogen, oxygen, acetylene, and metal powder in a chamber open at one end. When an electric spark detonates the mixture, the gas and powder particles leave the chamber at an explosive velocity. The particles, in a plastic state from the force of the detonation, strike and adhere to the base metal. The process is automatic, repeating 4 to 8 times per second. It takes place within a concrete structure because of the extreme noise that accompanies the detonations.

HVOF (high-velocity oxygen fuel) has become an important metal-spraying process. HVOF devices have an internal combustion chamber in which a mixture of fuel (propane, acetylene, hydrogen, or kerosene) is combusted with oxygen. The resulting products are expanded through a nozzle, where they attain supersonic velocity. Powder to be processed is axially injected into the hot, expanding gas, where it is heated and accelerated toward the substrate. Particle velocities can be in excess of 300 m/s (1000 ft/s) with gas temperatures of approximately 2100°C (3800°F). Because of this high velocity, the particles form a nearly fully dense coating on the substrate. The high temperature of the combustion process limits the materials that can be sprayed. Figure 8.3.11 illustrates an HVOF spray gun in operation.

To accomplish adequate and reliable bonding with all these methods, the substrate must be conditioned properly. The first step is to clean the surface of dust, oil, and other foreign matter. Once cleaned, the surface is further prepared by one or more of several methods: (1) roughening by grooving, threading, undercut machining, knurling, or otherwise rough-machining with metal-cutting tools, (2) coarse-grit blasting, (3) application of an initial bond-coat material (grit blasting may precede bond coating if especially strong bonds are required), (4) placement of a number of studs in the area to be coated, and (5) sanding or grinding (used for hard-base materials). Preheating of the workpiece is also sometimes employed to improve adhesion of the coating.

If the materials used are reactive, these processes may be carried out in an inert-atmosphere chamber, sometimes at reduced pressure.

Masking is required to prevent the coating from adhering to areas where none is wanted. It is performed before surface roughening by grit blasting. Mask materials include tape, sprayed compounds, and metals.

Postcoating operations may be performed, depending on the nature and function of

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FIGURE 8.3.12 Piston ring with flame-spray-coated hard bearing material. (*Courtesy Metco, Inc.*)

the coating and the part. Fusion of the coating reduces porosity and improves uniformity and adhesion. It involves heating after coating to a temperature below the melting point of the coating and is a necessary step if combustion flame spraying of powdered material is used. Sealing with organic coatings is used to offset the porosity of most coatings, primarily when it is necessary to provide corrosion protection. Machining, grinding, and lapping provide better dimensional accuracy and surface finish than those of the unfinished coating. Sometimes nondimensional polishing is also carried out to provide a smoother coating.

TYPICAL CHARACTERISTICS AND APPLICATIONS

The sprayed deposit is usually between 0.05 mm (0.002 in) and 2.5 mm (0.100 in) thick, but it may be as much as 6 mm ($\frac{1}{4}$ in) and occasionally as much as 25 mm (1 in) thick.

Sprayed coatings are somewhat porous, the degree of porosity depending on the spraying method. Porosity is desirable in bearing applications because the pores in the coating act as reservoirs for lubricants. Porosity in combustion-flame coatings ranges from 6 to 13 percent, in plasma-arc coatings from 1 to 12 percent, and in detonation-gun coatings from $\frac{1}{4}$ to 1 percent.

Thermal-sprayed coatings tend to be considerably harder than the parent coating material and have superior wear properties. They generally possess low ductility and reduced tensile strength. Tensile stresses are present. Bonding is mechanical rather than metallurgical or chemical except with the detonation-gun process, which gives high bond strengths. Typical bond strengths of thermal-sprayed coatings range from 34 MPa (5000 psi) to over 69 MPa (10,000 psi).

Part size is seldom a limitation to the applicability of thermal-sprayed coatings. Large and unwieldy parts can be coated with portable equipment. Some part shapes, however, may not be suitable if the surface to be sprayed is inaccessible. For parts requiring coatings on inside surfaces, there are gun extensions that can be used if the bore is 50 mm (2 in) or greater.

Common uses for thermal-sprayed coatings are to provide corrosion protection, to provide wear-resistant surfaces, to salvage worn or undersized parts, to provide electrical contact and electrically conductive surfaces, and to provide heat-oxidation protection.

Wear-resistant coatings are an important application. Wear-resistant properties are of several forms:

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TABLE 8.3.3 Typical Thermal-Spray-Process Applications

Part name	Process	Coating material	Coating thickness, mm (in)	Surface finish, μm rms (μin rms)	Operating conditions
Feed rolls	Plasma	Tungsten carbide	0.05–0.10 (0.002–0.004)	3.8 (150)	Low load, dry rubbing
Compressor rods	Detonation gun	Tungsten carbide	0.25–0.30 (0.010–0.012)	0.13–0.25 (5–10)	Sliding wear
Vanes	Plasma	Chromium carbide	0.08–0.13 (0.003–0.005)	3.8 (150)	High temperature, fretting wear
Seal spacers	Detonation gun	Chromium carbide	0.20–0.25 (0.008–0.010)	0.025–0.08 (1–3)	High temperature, sliding wear
Pump sleeves	Oxyacetylene	Aluminum oxide	0.38–0.46 (0.015–0.018)	0.50 (20)	Ambient temperature, water and sand abrasion
Carbon graphite seals	Plasma	Aluminum oxide	0.20–0.25 (0.008–0.010)	0.25 (10)	High load, fretting wear
Snick plates	Detonation gun	Aluminum oxide	0.05–0.08 (0.002–0.003)	Various	Abrasive wear by synthetic fibers
Shaft sleeves	Oxyacetylene	Chromium oxide	0.38–0.46 (0.015–0.018)	0.63 (25)	Ambient temperature, various chemical solutions
Wire-drawing sheaves	Plasma	Chromium oxide	0.20–0.33 (0.008–0.013)	0.63–0.88 (25–35)	High-speed sliding wear
Abradable sheals	Oxyacetylene	Nickel-graphite	2.5 (0.100)	10 (400)	Temperatures up to 800°F
Various	Plasma	Nickel	Various		Used for buildup of salvageable parts

1. *Resistance to adhesive wear.* This is the wear that occurs when two materials come into intimate contact. Many soft bearing materials that resist this kind of wear can be applied by thermal spraying. Typical applications are bronze and babbitt bearings, piston guides, thrust-bearing shoes, hydraulic-press sleeves, and crosshead slippers. In general, compared with poured babbitt, thermal-sprayed babbitt has a higher load capacity, greater integrity, and better bond to base. It also allows thinner coatings.

There are also hard bearing surfaces that provide resistance to adhesive wear. Hard bearing materials are used when self-alignment is not important and when lubrication may be marginal. Typically, a molybdenum or molybdenum-containing coating is used to increase wear resistance and resist scoring. A typical hard bearing application is the piston-ring facing shown in Fig. 8.3.12. Other hard bearing applications are roll journals, antigalling sleeves, fuel-pump rotors, rudder bearings, and armature shafts.

2. *Resistance to abrasive wear.* Flame coatings are used to resist the abrasive effect of hard foreign particles such as metal debris, metallic oxides, and dust. Typical applications of this type of coating are grinding hammers, pigtails, slush-pump piston rods, buffing and polishing fixtures, reciprocating-pump plungers, and pump drive shafts.

3. *Resistance to surface-fatigue wear and cavitation.* Flame-sprayed coatings that resist the surface cracking and chipping that can result from repeated cyclic stresses are available. These coatings also resist the mechanical shock caused by cavitation in liquid flow. Typical applications of these coatings are valve faces, jet engine compressor-blade midspan supports, rocker arms, expansion joints, water turbine nozzles, pumps, and impeller blades.

4. *Resistance to erosion.* This is closely analogous to resistance to abrasion, except that the abrasive particles are carried by a gas or a liquid. Coatings for these conditions are available for temperatures from ambient to 840°C (1550°F). Typical applications are cyclone dust collectors, hydroelectric valves, exhaust-valve seats, and exhaust fans.

Table 8.3.3 lists typical flame-spraying applications with the coating material and process used and the coating thickness.

ECONOMICS OF PRODUCTION

Initially, thermal spraying (metallizing) was used almost entirely as a repair process for replacing metal on worn parts. However, recognition gradually was given to its applicability to production conditions as well. Production applications are becoming more common as original parts are designed for sprayed coatings.

Equipment costs for flame spraying are modest. Tooling expenses are low also because only simple holding fixtures and masks, if required, are involved. Therefore, high production levels are not required to amortize investments for production apparatus. However, when high production levels are required, the operation can be mechanized to minimize labor costs.

Metal deposition rates normally range from 1.6 to 4.5 kg/h (3.6 to 9 lb/h). This is equivalent to a range of 1.3 to 6.6 m^2/h per 0.1 mm of coating thickness (57 to 280 ft^2/h per 0.001 in of thickness). Note that these figure do not include an allowance for overspray. With electric-arc deposition of nickel alloys, however, rates as much as 10 times these have been achieved.

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Thermal spraying, including preparatory and finishing operations, has relatively high unit costs. It is most applicable when the workpiece itself is costly or critical to the function of the final product.

Metallizing (combustion thermal spraying) is the least costly thermal-spraying method. However, the bond strength of the coating is lower than with the plasma-arc and detonation-gun methods. The electric-arc method is in common use for zinc corrosion-resistant coatings and other low-cost applications. Detonation-gun spraying is most costly but provides the best coating properties. It requires a large-scale operation to be cost-effective because of the greater investment required, largely for soundproofed protected facilities, and the need for remote-controlled automatic operation.

SUITABLE MATERIALS

Coatings

Almost any material that can be melted without decomposing can be thermal-sprayed. Standard sprayable materials can be classified as follows:

1. *Pure metals.* Aluminum, zinc, nickel, refractory metals, etc.
2. *Alloys.* Steel, cobalt- and nickel-based superalloys, hard-surfacing and self-fluxing alloys, etc.
3. *Compounds.* Aluminum oxides and other metal oxides, carbides, cermets, and nitrides, etc.
4. *Composites and blends.* Admixtures and combinations of two or more of the above in a single powder. Cobalt-bonded tungsten carbide and nickel-clad graphite are two examples.

Any material that melts into droplets (glass forms strands rather than droplets) and which can be put into wire form can be sprayed by the combustion-flame-spraying (wire-metallizing) method. Metals commonly sprayed by this method include zinc and aluminum (the most common), brass, bronze, copper, tin, lead, magnesium, molybdenum, nickel, babbitt, cadmium, carbon steels, alloy steels, and stainless steels.

Flame coating from powder is applicable to hard, corrosion-resistant alloys, notably those cobalt- and nickel-based alloys that contain chromium, silicon, and boron. Powder spraying is also suitable for low-melting-temperature ceramic materials and plastics. Low-melting temperature metals such as zinc, tin, and aluminum are sprayed from powder, but wire-metallizing of these materials is faster and more efficient.

Plasma coating is applicable to practically an unlimited series of materials. Refractory metals such as tungsten, tantalum, and molybdenum are routinely handled by the plasma methods. Other materials that can be coated by plasma-arc spraying include carbides, borides, oxides, nitrides, beryllides, silicides, and sulfides, pure metals and alloys, plastics, glass, and various blends. Plasma spraying is particularly useful when high-melting-temperature materials such as carbides and ceramics are to be sprayed or when it is necessary to avoid oxide contamination of metal coating particles.

Detonation-gun spraying is best for hard surfacing with tungsten carbide, aluminum oxide, chromium carbide, and similar materials.

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Substrates

These are usually metal but can be ceramic, glass, concrete, plaster, carbon, or even wood, plastic, rubber, or cloth. The cooling effect of the airstream prevents heat damage to temperature-sensitive materials. However, with the detonation-gun process nonmetallic substrates are not suitable because of erosion from high-velocity particles.

Both nonferrous and ferrous metals are thermal-spray-coatable. Hard surfacing of nonferrous substrates is a common application. Resulfurized and leaded steels are not recommended because the additives embrittle the metallic coating. Hardened steel can be coated but is more difficult to surface-roughen prior to coating than unhardened steel. Also, low-carbon steels are generally preferable to high-carbon steels as substrate materials.

Bonding Coatings

These materials adhere to a clean, smooth surface that does not have to be mechanically roughened or grit-blasted, although grit blasting may be performed. The top coating is then sprayed over the bonding coating. This approach has a major advantage besides the reduction of precoating surface preparation, which can be costly and can adversely affect the workpiece. Added insurance against bond failure is provided. This is important in many applications, for example, when it is necessary to machine or grind the coating to a featheredge. Molybdenum is the major bond-coating material. Nickel-alu-

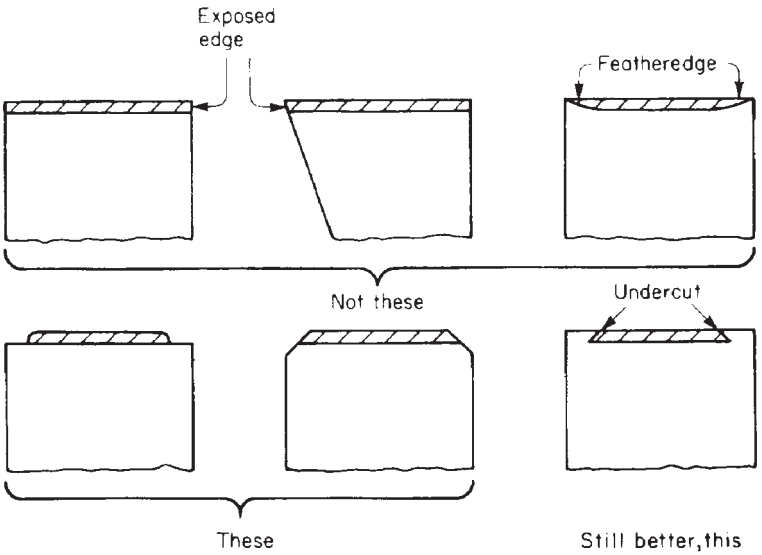

FIGURE 8.3.13 Avoid exposed edges of flame-sprayed coatings and also featheredges. Surfaces held by undercuts at the edges are best.

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TABLE 8.3.4 Coatings for Hard Bearing Applications*

Coating process†	Description and chemistry	Hardness	Finish, μin AA†	Maximum service temperature, °F	Comments
APS PC	Nickel, 55 iron, 5 Mo, 5 Al, composite powder	R_b 90 to R_c 25	AS, 400–700 G, 15–30 L, 4–10 M, 25–45	700	Excellent bond and machinability, APS coating powder, harder than PC
PC	Nickel 7% Mo, 6% Al, composite powder	R_b 90	AS, 300–400 M, 40–60	900	Best bonding, poor machinability, good corrosion resistance
APS PC	Nickel, 20% chromium, 5% molybdenum, 6% Al, composite powder	R_b 90	AS, 400–500 M, 20–30 G, 15–20 L, 4–7	1200	High-temperature service, good bonding
HVOF	Tungsten carbide, 12% Co, composite 41-μm particles	R_c 60	AS, 175–200 L, 1–3	1000	Best wear resistance, high surface finish, needs diamond grinding
APS	Tungsten carbide, 12% Co, blended with 50% nickel-base fluxing alloy	R_c 50–55	AS, 200–300 L, 2–4	1000	Can be HVOF sprayed to get improved properties
WC	Molybdenum wire, 99.9% Mo	R_c 40	G, 50–100	650	One coat of self-bonding high-scuff-resistant bond coating

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PC NC	Iron, chromium, nickel, stainless steel, powder or wire	R_b 90	AS, 300–400 M, 40–50 G, 10–20 L, 5–10	1400	Machinable 315 stainless steel coating
WC EA	High-chromium stainless steel wire, 0.35% C, 0.02% P, 0.02% S, 2% Mn, 8% Ni, 18% Cr, 0.75% Si, balance Fe	R_c 33	G, 25–50	1000	Hard grindable 420 stainless steel coating, bond coat or other surface preparation required

*Including one-coat self-bonding coatings.

†AS = as sprayed; G = ground; M = machined; L = lapped; APS = air plasma spray; HVOF = high-velocity oxygen fuel spray; EA = electric-arc spray; WC = wire combustion spray; PC = powder combustion spray (low velocity).

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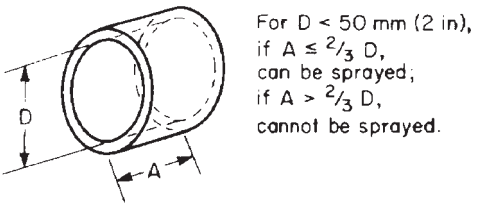

FIGURE 8.3.14 Limitations on the depth of internal surfaces that can be flame-sprayed.

minum composites (Metco M405-10, T or P404-10, and T or P450-10, 11) are also used quite extensively.

These bonding coatings adhere well to the following materials: all common steels including hardened alloy steels and 300 and 400 Series stainless steel, nickel and cobalt and their alloys, cast iron and cast steel, titanium and aluminum and their alloys, brass and Monel. They do not reliably self-bond to copper and some copper alloys, molybdenum, tantalum, niobium, and tungsten.

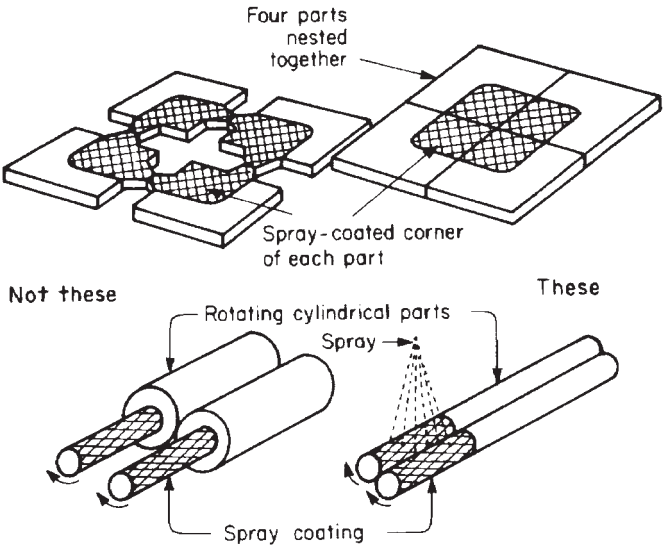

FIGURE 8.3.15 Design parts so that they can be nested together during flame spraying to reduce overspray losses.

DIMENSIONAL FACTORS AND TOLERANCE RECOMMENDATIONS

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TABLE 8.3.5 Recommended Minimum Thickness of Thermal-Sprayed Coatings on Shafts

Shaft diameter, mm (in)	Minimum coating thickness per side, mm (in)
25 (1) or less	0.25 (0.010)
25–50 (1–2)	0.38 (0.015)
50–75 (2–3)	0.50 (0.020)
75–100 (3–4)	0.63 (0.025)
100–125 (4–5)	0.76 (0.030)
125–150 (5–6)	0.89 (0.035)
150 (6) or more	1.0 (0.040)

Source: Data taken from ASM Committee on Metal Spraying, "Metal Spraying," *Metals Handbook,* vol. 2, 8th ed., Lyman Taylor (ed.), American Society for Metals, Metals Park, Ohio, 1984, p. 509. Values are based on average conditions of wear and include an allowance for finish machining after flame spraying.

DESIGN RECOMMENDATIONS

The following comments are offered to guide the design engineer in specifying sound coatings. A sprayed coating will not impart structural strength to the base material. Proper design should anticipate this and the part made to withstand anticipated forces without the coating. Generally, the designer should use a bond coat, but this is not always practical; therefore, a few guidelines are listed. However, do not consider these to be hard and fast. There may be specific instances in which they cannot be followed.

1. When the primary coating *is not self-bonding,* the coating is applied with the plasma gun, and the design requires a coating thickness less than 0.25 mm (0.010 in), use a blasted surface only. If the application requires a coating thicker than 0.25 mm, use a bond coat. Then apply the topcoat.

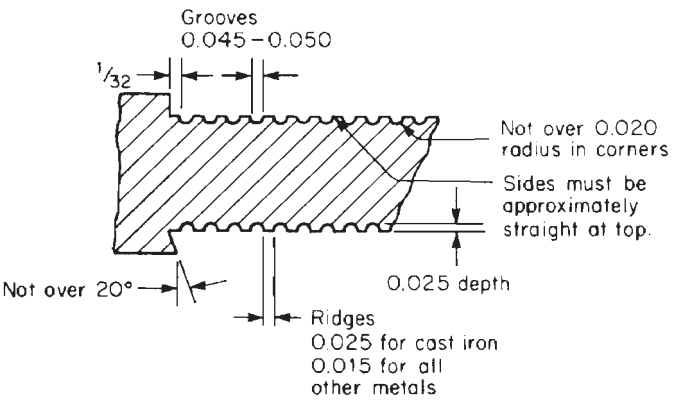

FIGURE 8.3.16 A recommended design for grooving a shaft to ensure strong adhesion of flame-sprayed coatings. Dimensions shown are in inches. Grooves can be either annular or helical. Knurling at the tops of the ridges produces a dovetail undercut that further ensures a strong bond.

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2. For machine-design work, when the primary coating is not self-bonding and is applied with a wire or powder combustion gun, always design with provision for a bond coat. If less than a 0.25-mm (0.010-in) coating thickness is needed, use an undercut greater than 0.25 mm to allow for the thickness of a bond coat.
3. When very thick coatings are required, it is sometimes advisable to use a low-cost intermediate coat between the bonding coat and the functional topcoat. The bond coat should be 0.075 to 0.12 mm (0.003 to 0.005 in) thick. Coating materials should be selected to avoid galvanic corrosion between layers.
4. Some coatings that possess both the favorable adhesion of bonding coatings and the functional properties of topcoatings are now available. With these materials, no separate bonding coating is required. Some of these materials are listed in Table 8.3.4. Their use is recommended.

Because of the brittleness of flame-sprayed coatings, they should not be used when the function requires point contact or when the coating will be exposed to sharp blows, continued pounding, or severe strain at an edge or in a small area. Examples of this kind of condition are gear teeth, journals running against needle bearings, impact faces of hammers, and rolling-mill ways. Journals, plain bearings, hydraulic rams, crankshafts, piston sleeves, and machine-tool ways are examples of components which have the load on the coating evenly distributed.

Sprayed coatings are also susceptible to chipping at the edges because of sudden blows either in service or during handling. For this reason, it is best to provide an undercut at the end of the coating. Thus, when the coating has been machined flush, no raw edges are exposed. (See Fig. 8.3.13.)

When coatings are needed on internal surfaces, there are limitations to the depth that can be sprayed. If the opening is large enough for a spray-gun extension, there is no length limitation; otherwise, the maximum coating depth is two-thirds of the diameter of the opening, as shown in Fig. 8.3.14.

For best results in production, the workpiece should be designed to facilitate handling. For example, a cylindrical part should, when possible, include in its design a means by which it can be rotated: centers, flanges, etc. A sheet-metal stamping could be only partially sheared through to allow handling a continuous strip rather than individual parts at the spraying operation. Irregular parts should include a locating hole or other means for easy orientation.

To reduce the costs of oversprayed material and increase the rate of production, it is common practice to design parts for nesting as illustrated in Fig. 8.3.15.

For coated parts to be press-fitted, the coating should be at least 0.13 mm (0.005 in) thick to ensure adequate strength. For rotating shafts, recommended minimum coating thicknesses for average conditions of wear and finish machining are given in Table 8.3.5.

Deposits on internal surfaces should be kept to minimum thickness. Because of the shrinkage forces inherent in flame-sprayed coatings, thick coatings on internal surfaces are apt to separate from the workpiece. However, extremely thin coatings should not be specified for internal or external surfaces. Coatings under about 0.08 mm (0.003 in) are not recommended because thickness uniformity cannot be controlled sufficiently.

As indicated above, a roughened or grooved surface is advisable to ensure adequate adhesion of the flame-sprayed coating. Figure 8.3.16 illustrates the recommended groove design for a shaft that is to be coated.

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DIMENSIONAL FACTORS

The surface finish of flame-sprayed coatings ranges from 1.0 to 10.0 μm (40 to 400 μin) rms. Careful machining, grinding, lapping, etc., can reduce the roughness after machining to normal values achievable with materials of lower machinability.

The surface finish and the accuracy of coating thickness depend on a number of factors. One major factor is the uniformity of speed of spray-gun movement. Hand-held guns produce much more variation than machine-mounted guns. The nature of surface preparation is an important determinant, with blasted surfaces providing more uniformity than deeply grooved surfaces. Shrinkage of coating material also must be allowed for. This varies with different materials but ranges from about 0.15 percent to about 1.2 percent.

The normal variation of coating thickness under controlled production conditions ranges from about 0.05 mm (0.002 in) to about 0.13 mm (0.005 in) in total variation.

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PART 3
VACUUM-METALLIZED SURFACES

THE PROCESS

Vacuum metallizing is a process in which thin coatings of metals or metal compounds are deposited on workpiece surfaces in a vacuum chamber. The coating material is heated to the point of evaporation. The vapors condense on the cooler workpiece surface and solidify. The entire process takes place within a closed chamber having a vacuum of 10^{-3} to 10^{-5} mbar. Workpieces are located on racks surrounding the source of the vapor, which is centrally located. The vapor travels only in a straight line, but the workpiece can be rotated if coverage is required on more than one side. Proper positioning of the workpiece is very important.

The material to be deposited is heated by electrical resistance, induction, or electron beam. The resistance method, however, is most common.

Because of the high vacuum levels required, the process must operate on a batch basis except for strip materials, which can be passed through vacuum seals.

Proper adhesion of the coated material demands that the workpiece surface be thoroughly cleaned. Vapor degreasing is the most common method. Many parts are precoated prior to metallizing. The precoat provides a smoother substitute for the metal coating and, for some base materials, seals the escape of volatile substances which would interfere with the coating process. After the metal-coating operation, a protective lacquer or other nonmetallic coating is often applied for corrosion and abrasion protection. Plastic parts receiving decorative coatings do not usually require extensive precleaning but are given a base coat and a clear protective coating.

Vacuum chambers range from one to several hundred cubic feet in size.

TYPICAL CHARACTERISTICS AND APPLICATIONS

There are five basic applications for vacuum coatings:

1. *For decoration.* A bright, lustrous metallic coating is applied to plastic components, film, or paper.
2. *For optical applications.* A thin film is applied, normally to optical glass to provide reflectance or, with closely controlled film thickness, light attenuation (e.g., sunglasses), filtering, or beam splitting.
3. *For corrosion protection.* Although less used for this application and usually inferior for corrosion protection to electroplated coatings, vacuum coatings are used for some corrosion-protection applications.
4. *For electronics and electrical applications.* Capacitors, integrated circuits, contacts, and photoconductors utilize vacuum coatings.
5. *For encapsulation of powdered materials.*

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TABLE 8.3.6 Typical Applications of Vacuum-Deposited Coatings

Coating material	Function	Coating thickness, mil	Substrate material	Pretreatment	Post-treatment
Aluminum	Decorative	0.001–0.005	Metal[a]	Lacquered	Lacquered
Aluminum	Reflective	0.001–0.005	Glass	None	[b]
Aluminum	Protective	0.5	Steel	None	Anodized[c]
Aluminum	Decorative	0.001	Plastic sheet	None	Laminated
Aluminum	Decorative	0.5	Aluminum[d]	None	Anodized
Aluminum	Electrodes[e]	0.0005–0.001	Plastic shot	Baked	None
Cadmium	Protective	0.5	Steel	None	Painted[e]
Cadmium	Electrical resistance	0.0001–0.001	Glass or plastic	None	Multiple layers
Chromium	Electrical resistance	0.0001–0.001	Glass or plastic	Cleaned	Air-baked
Gold	Electrodes for piezoelectric crystals	0.001–0.005	Organic or m inorganic crystals	Cleaned	None
Magnesium fluoride	Nonreflective	0.004	Glass	None	None
Silicon monoxide	Abrasion resistance	0.004	Glass	[b]	Oxidized
Titanium dioxide	Decorative; optical	0.004	Glass	None	Oxidized
Zinc	Electrical conductivity	0.001–0.005	Paper	Lacquer	None

[a]Automotive trim. [b]Aluminum coating for reflectance followed by silicon monoxide coating for abrasion resistance for mirrors. [c]If required. [d]Die casting. [e]For capacitors.

Source: ASM Committee on Vapor Deposition Coating, "Vacuum Coating," *Metals Handbook,* vol. 2, 8th ed., Lyman Taylor (ed.), American Society for Metals, Metals Park, Ohio, p. 517.

The coating finish can be brilliant and requires no buffing if the substrate surface is smooth. Coatings are normally on the first surface (top side) of a component, but in the case of clear materials they can be applied to the second surface (rear side). This provides full abrasion protection to the coating and a very rich, jewel-like look to the decorated product.

Typical components receiving decorative vacuum coatings are costume jewelry, toys, home appliances, hardware, automotive trim (normally interior), decorative nameplates, and various sheet materials. Optical applications include mirrors, automobile headlights, flashlights and other reflectors, telescopes, microscope filters, sunglasses, optical filters and other instruments, beam splitters, and other objects requiring some degree of light reflection. Also included in this classification are reflective coatings for infrared and longer-wave thermal energy.

The most notable anticorrosion application of vacuum coating is in food containers, for which tin can be applied by vacuum methods more economically than by electroplating. Aluminum-coated steel is used for packaging applications. An advantage of vacuum coating over electroplating for highly stressed parts is the absence of hydrogen embrittlement. Cadmium and aluminum vacuum-applied anticorrosion coatings average from 5 to 10 μm (0.2 to 0.4 mil) in thickness. Vacuum-applied aluminum improves the corrosion resistance of galvanized steel.

Electrical and electronic applications of vacuum coating are quite varied and are growing rapidly. Capacitors are perhaps the largest-volume application, using tanta-

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TABLE 8.3.7 Electronic Applications of Vacuum-Deposited Metals and Metal Compounds

Coating material	Application	Coating thickness, μm
	Metals	
Aluminum	Conductor[a]	0.01–0.2
Bismuth	Conductor[b]	0.05–0.5
Cadmium	Conductor	0.05–1
Chromium[c]	Resistor	0.002–0.1
Columbium (niobium)[d]	Superconductor	0.05–0.1
Copper	Conductor	0.01–0.2
Germanium[d]	Semiconductor	0.5–1.0
Gold	Conductor	0.01–0.2
Indium	Conductor	0.05–0.2
Lead	Conductor	0.05–0.2
Molybdenum	Conductor[e]	0.05–0.2
Nickel	Conductor	0.05–0.2
Platinum[f]	Conductor	0.01–0.2
Selenium	Semiconductor	0.5–100
Silicon[d]	Semiconductor	0.5–10
Silver	Conductor	0.01–0.2
Tantalum[f]	Resistor	0.01–0.2
Tin	Superconductor	0.05–0.2
	Metal compounds	
Aluminum oxide[f]	Capacitor	0.1–2
Cadmium sulfide	Semiconductor; photoconductor	0.1–2
Cerium oxide	Capacitor	0.1–2
Silicon oxide	Capacitor; insulator	0.1–2
Tantalum oxide[g]	Capacitor	0.01–0.2
Titanium oxide[h]	Capacitor	0.03–0.2
Zinc oxide	Semiconductor	0.1–2

[a]Good counterelectrode for capacitors. [b]Good counterelectrode for rectifiers. [c]Adheres exceptionally well to glass. [d]Difficult to obtain purity desired. [e]Good conductor for high-temperature applications. [f]Difficult to vaporize except by electron-bombardment heating. [g]Produced by anodizing tantalum films. [h] From thermal oxidation of titanium metal.

Source: ASM Committee on Vapor Deposition Coating, "Vacuum Coating," *Metals Handbook,* vol. 2, 8th ed., Lyman Taylor (ed.), American Society for Metals, Metals Park, Ohio, p. 517.

lum, titanium, silicon monoxide, and magnesium fluoride coatings on paper, plastic film, and glass. Integrated circuits lean heavily on vacuum-coating techniques to deposit conductive, semiconductive, and resistive materials. Magnetic tapes are another major application. Magnetic iron-nickel and other alloys are vacuum-deposited on plastic film. For conductors and contacts in various electrical and electronic devices, conductive metals like gold, silver, copper, tin, platinum, and iridium are vacuum-deposited. An additional application is the deposition of copper on nonconductive surfaces to provide a base coat for electroplating or electroforming.

Vacuum-deposited coatings are generally of high purity and density. While thin coatings are lustrous, thicker coatings of 2.5 μm (0.1 mil) or more tend to be gray or wavy in appearance. Normal coatings are from 0.05 to 10 μm (0.002 to 0.4 mil), with the thin coatings for decorative applications and the thick coatings for corrosion-protection applications. Metal coatings 0.08 to 0.1 μm (0.003 to 0.004 mil) thick are opaque.

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The maximum size of component that can be vacuum-coated depends on the size of vacuum chamber available. See Tables 8.3.6 and 8.3.7 for summaries of applications of vacuum coatings.

ECONOMIC PRODUCTION QUANTITIES

For maximum economy of production of vacuum-coated parts, quantities should be large. The process is not limited to mass production, and for many applications, primarily in the optical and electronics industries, vacuum coating is the only process that can provide coatings of the correct controlled thickness. However, for decorative applications electroplating is a competing process that may be more economical in some situations, especially when production quantities are small. For large production volumes, if the product configuration lends itself to vacuum coating, the vacuum process is invariably lower in cost.

Unit costs for decorative coatings comprise primarily the handling labor to load and unload the chamber and to apply the precoat and topcoat. Lacquer coating materials are far more costly than the aluminum usually employed for decorative coating. However, tungsten filaments used to provide the heat for vaporizing the coating material also often comprise a significant portion of the total unit cost.

Processing times for decorative coatings run about 15 min per batch in large (2-m-diameter) chambers, most of which is pump-down time for the vacuum. The actual coating cycle on the chamber (e.g., for aluminum) is about 60 s. Heavy coatings for corrosion protection require more time, with a total cycle of approximately 50 to 90 min.

SUITABLE MATERIALS

Aluminum is by far the most common vacuum-coated material. It accounts for over 90 percent of decorative coatings and may be used for optical, electronic, or corrosion-protection purposes also. Aluminum has a high vapor pressure; i.e., it vaporizes easily at lesser vacuum levels. It also has an attractive appearance and high reflectivity when used as a coating. After aluminum, in order of decreasing vapor pressure (the most important factor in vacuum coatability), are selenium, cadmium, silver, copper, and silicon monoxide. A second group, again in order of decreasing vapor pressure, are gold, chromium, palladium, nickel-chromium alloy, magnesium fluoride, and titanium. Other materials, considerably less volatile, that have been vapor-deposited are platinum and niobium.

Actually, almost all metals, many alloys, and many semimetallic elements can be vacuum-deposited. However, materials that do not vaporize easily present difficulties in processing because very high vacuum levels are necessary and processing costs multiply.

Certain compounds of metals and other elements are useful as coatings and can be deposited by vapor-deposition methods. Silicon monoxide is the most commonly used of such compounds. It provides an abrasive-resistant finish over aluminum and is often applied immediately after the deposit of aluminum without interrupting the vacuum. Magnesium fluoride and aluminum oxide are used in the manufacture of electronic capacitors.

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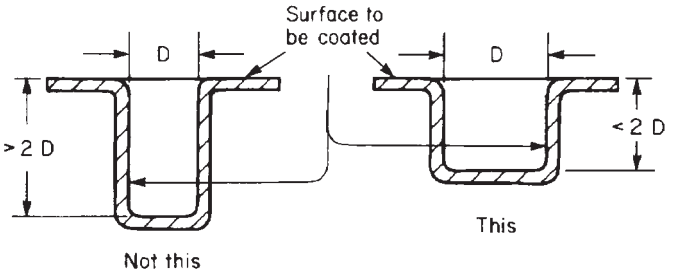

FIGURE 8.3.17 Deep recesses in the surface to be coated should be avoided.

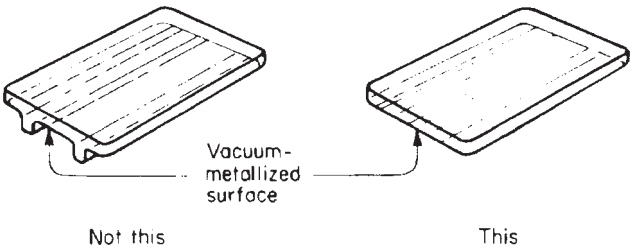

FIGURE 8.3.18 When the second (rear) surface is to be coated, the thickness of the part between both surfaces should be uniform.

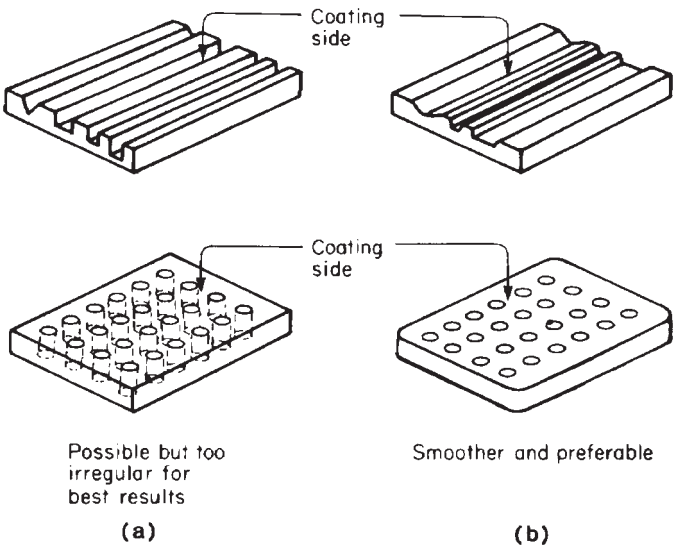

FIGURE 8.3.19 Regular surfaces are preferred for vacuum coating and should be specified whenever possible.

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OTHER METALLIC COATINGS

Alloys and compounds sometimes present difficulties in uniformity of coating composition. These coating materials can fractionate during heating; more volatile constituents tend to vaporize first and condense on the workpiece separately before less volatile materials.

A variety of substrate materials can be vacuum-coated. The fact that electrical conductivity is not required permits many nonmetallic materials to be coated. The one essential requirement of a base material is that it be relatively stable in a vacuum. It must not give off gases or vapor. Gases may come from contaminants on the surface of some parts, may be trapped in the pores of the base materials, or may result from the evaporation of an ingredient in the base material.

Metals usually are satisfactory as substrates. However, zinc-based alloys and brass (because of the zinc content) are not suitable for heavy protective deposits, although they can be coated with thin decorative coatings. Many nonmetallic base materials that would not be satisfactory normally can be made suitable for the application of a base coating. Common substrate materials are glass, ceramics, silicon and germanium (semiconductors), most plastics (polystyrene, acrylic, polycarbonate, acrylonitrile butadiene styrene, styrene acrylonitrile, urea, melamine, phenolic, polyester, and epoxy), steel, copper, and other metals, and paper. Normally, vinyl and cellulosics are not recommended because of gassing, and polyolefins (polyethylene and polypropylene) require pretreatment of the surface to improve the adhesion of the coating.

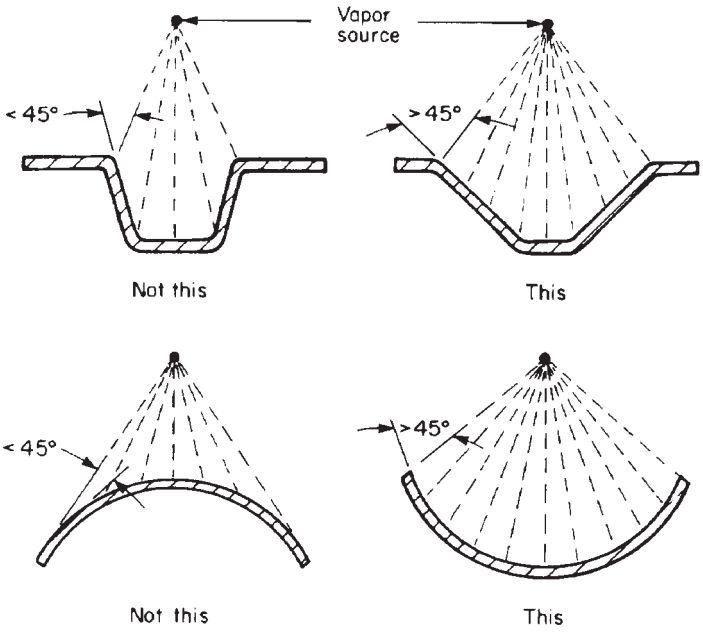

FIGURE 8.3.20 The angle of the part's surface and the line-of-sight path of the vapor should not be less than 45°.

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DESIGN RECOMMENDATIONS

Design recommendations for vacuum-coated components stem from two factors:

1. The need for an enclosed vacuum chamber with its inherent size limitations
2. The line-of-sight travel path of coating vapor from source to workpiece

The following are specific design recommendations arising from these factors:

1. Parts should be as compact as possible to enable a large number to be placed in the vacuum chamber. Arms and other extensions that may interfere with the placement of other workpieces or with holding fixtures should be avoided. It may be desirable to separate a large component into two parts for later assembly if only one portion of the large component is to be vacuum-coated.
2. Deep recesses and holes should be avoided in surfaces to be coated. Holes up to two diameters deep generally coat satisfactorily. Holes and recesses up to five diameters (or widths) deep often can be coated also but with a thin layer only. (See Fig. 8.3.17.)
3. When a decorative coating is applied to the second surface of a component, ribs, bosses, or other appendages that affect the thickness of the part as measured from the first surface will affect its appearance. Thicker sections will show up with a darker shade. For best appearance, the thickness of the part between the first and second surfaces should be uniform. (See Fig. 8.3.18.)
4. Coating the interior surfaces of hollow parts is difficult unless the interior of the workpiece is large enough to contain the filament or other source of evaporated metal. This is normally a more expensive procedure because more vapor sources are required (except perhaps in the case of large parts), and exterior surface coating is therefore usually preferable.
5. Irregular surfaces such as are illustrated in Fig. 8.3.19*a* require multiple sources of metal evaporation to ensure coverage of all areas. In addition, they are more difficult to spray with precoat lacquer. More regular surfaces as illustrated in Fig. 8.3.19*b* are preferable and should be specified whenever possible.
6. Fixtures that rotate the workpiece so that it is coated on more than one side are more costly than those that simply hold the workpiece for coating on one side. One-side coatings should be specified whenever possible.
7. Angles of incidence between the line-of-sight path of the vapor and the workpiece surfaces should not be shallower than 45°. Recesses should have as gently sloping walls as possible. (See Fig. 8.3.20.)
8. Optical parts and others with a surface smooth enough so that the vacuum coating can be deposited directly on the substrate without necessity for a precoat should be designed so that precleaning solvents can drain easily from the surface.
9. While highly irregular surfaces are not desirable for vacuum coating, large flat surfaces may cause problems too if the material is such that a lacquer precoat is required. It is sometimes difficult to spray a smooth coating over a large surface and maintain a uniform appearance. Either extra care must be taken in the lacquer application, or the surface should be made smaller or lightly textured in certain areas.

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OTHER METALLIC COATINGS

While coating thickness can be controlled quite closely, there are normally variations in part-to-part coating thickness and in the thickness on one workpiece. These result from a number of process variables. The major variables are an inherent nonuniformity in the dispersement pattern of vapor from the source, irregularities in shape of the workpiece surface, and the shadow effect which results when the supporting frame comes between the workpiece and the vapor source. Rotation of the workpiece averages out the latter variations. Thickness is usually controlled by controlling the process parameters: filament size and current, coating-metal clip size, degree of vacuum, and vaporization time.

Decorative and simple reflective coatings usually have a wide allowable thickness latitude, as much as ±50 percent. Electronic and optical filter applications, on the other hand, require very close thickness control, often ± 5 percent and, in some cases, to ±1 or ±2 percent. Such close control is more expensive and involves extra process steps to develop and maintain process parameters within narrow limits. For normal product applications, the following nominal dimensional ranges are recommended: decorative and simple reflective coatings, 0.05 to 0.13 μm (0.002 to 0.005 mil); corrosion-protection coatings, 5 to 10 μm (0.2 to 0.4 mil).

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